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A Correlation of Outer Radiation Zone Electrons ($E_e \sim 1$ MeV) with the Solar Activity Cycle*

by

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Abstract

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A comparison of observations with several earth satellites reveals that the inner edge of the outer radiation zone of electron $E_e > 1.6$ MeV intensities has moved outward from $L \simeq 2.2$ in mid 1958 to $L = 3.0$ in late 1964. This outward motion of the outer radiation zone occurs during the declining phase of solar activity cycle 19 and strongly suggests a systematic change of the average value of one or more of the solar wind parameters over this time period.

Author

Introductory Comments

Measurements of the radiation belts surrounding the earth have now been performed over a substantial fraction of a solar activity cycle, the descending portion of solar cycle 19, with earth satellites and space probes beginning with the discovery of the geomagnetically trapped radiation with the instrumentation of Explorer 1 launched on 1 February 1958. The sun is now believed to be the predominant, primal source of energy required to maintain the radiation belts surrounding the earth--at least beyond an equatorial geocentric radial distance of about 2 earth radii--via the flow of solar corpuscular energy, or solar wind, past the earth. Thus it is of interest to combine the data from a number of satellites and space probes flown during the past seven years for an investigation of changes in the structure of the outer radiation zone during a solar activity cycle. One such study is reported here using an essentially homogeneous body of data obtained from similarly shielded (~ 1 g cm^{-2}), nominally identical Geiger-Mueller tubes which respond primarily to electrons $E_e \gtrsim 1$ MeV in the outer radiation zone [O'Brien, Van Allen, Laughlin, and Frank, 1962; Frank, Van Allen, and Hills, 1964], and which have been flown by us on Explorers 4, 7, 12, and 14; Injuns 1, 3, and 4; Pioneers 3 and 4; and OGO 1.

A Parameter for the Determination of the Long Term Variation

The profiles of electron ($E_e \gtrsim 1$ MeV) intensities in the outer radiation zone are characterized by marked temporal changes in gross structure and intensities in association with variations in geomagnetic activity as measured, for example, by the planetary magnetic indices Kp. Typically, during a geomagnetic storm cycle the intensities of electrons ($E_e \gtrsim 1$ MeV) fluctuate by a factor of ~ 100 and the position of the outer zone maximum intensity varies over a range of $L \simeq 3.0$ to 5.0 [Forbush, Pizzella, and Venkatesan, 1962] [Frank, Van Allen, and Hills, 1964]. Thus, in order to study variations of these profiles over a period of several years, it is necessary to find some characteristic of the signature of the outer radiation zone which is relatively insensitive to short time-scale (~ 1 month) perturbations. A feature of the intensity profiles utilized here is exemplified by the Explorer 12 data of Figure 1. Shown are three contours of the type 302 G.M. tube response for three similar Explorer 12 passes through the so-called 'slot', or minimum count-rate region at $L \simeq 2.6$ between the outer radiation zone at higher L-values and inner radiation zone (protons, $E_p \gtrsim 20$ MeV) at the lower L-values. Although these data were taken over a period of ~ 1 month during which the outer zone maximum intensity changed markedly, the stability of the position of the inner edge of the outer radiation zone of electrons ($E_e \gtrsim 1$ MeV) at L = 2.6 ($\pm$ 0.1) indicates that this parameter is appropriate for our present investigation of long term variations. Similar analyses of 302 G.M. tube data from Explorer 4 [Van Allen, McIlwain, and Ludwig, 1959], Pioneer 3 [Van Allen and Frank, 1959a], Explorer 7 [Forbush, Pizzella, and Venkatesan, 1962], Explorer 14 [Frank, Van Allen, and Hills, 1964], Injun 3 [Craven, 1966], and OGO 1 [Frank, Van Allen, Hills, and Fillius, 1965] are summarized in Figure 2. Note that data from both high and low eccentricity satellites and from space probes are combined in a single plot, and that determinations of the inner edge of the outer radiation zone as discussed above during similar periods for both high, eccentric and low, circular orbiting satellites are identical within experimental error (compare Pioneer 3 and Explorer 4, Explorer 14 and Injun 3). Electron ($E_e > 1.2$ MeV) measurements with a solid state, electron integral spectrometer on satellite 1963 38C [Williams and Kohl, 1965] have been included for comparison with the G.M. tube data. Figure 2 shows that the inner edge of the outer radiation zone has shifted from L $\simeq$ 2.2 in mid 1958 to L $\simeq$ 3.0 in late 1964, or Δ L $\simeq$ 1 over an approximately six-year period. The gross nature of declining solar activity is represented by the parallel plot of smoothed sunspot numbers for this time period [Central Radio Propagation Laboratory Bulletin-F, Part B, issued January 1965] in Figure 2. The Explorer 14 and Injun 3 measurements shown in the summary graph may be artificially high due to the residual radiation injected by the three Soviet nuclear bursts during late October--early November 1962.

It may be inquired whether, for our present definition of the position of the inner edge of the outer radiation zone (Figure 1), the effect displayed in Figure 2 might be merely a manifestation of an increasing base-line 'slot' counting rate over the period of observations. Reference to the literature quoted above shows, however, that the 'slot' responses of the 302 G.M. tube at a given geomagnetic latitude are approximately constant or slowly decreasing over this time interval, thus producing a negligible, or slightly contrary effect.

Upon consideration of the above observational evidence we conclude that the inner edge of the outer radiation zone has shifted from $L \simeq 2.2$ to $L \simeq 3.0$ over the period 1958-1965 during the declining phase of the solar cycle.

Discussion

The most significant early study of the temporal variations of the electron distribution in the outer radiation zone is that of Forbush, Pizzella, and Venkatesan [1962]. These authors found a systematic negative correlation between the L value of the maximum outer zone intensity (L_{max}) and the geomagnetic U-index during the period October 1959 to December 1960. The observed value of L_{max} lay in the range 2.6 to 4.7, with a median value ~ 3.5. During 1963, Armstrong [1965] found L_{max} to have a median value ~ 4.0 with Injun 3; and during late 1964, Frank et al. [1965] found $L_{max} \sim 4.5$ with OGO 1.

It is suggested that the outward movement of the inner edge of the outer zone by $\Delta L \sim 1.0$, as reported herein, and the outward movement of the peak intensity of the outer zone, also by $\Delta L \sim 1.0$, during approximately the same time period of declining solar activity are complementary consequences of the same basic cause--namely a systematic change of the average value of one or more of the solar wind parameters, density, bulk velocity, temperature, and magnetic field strength [cf. Snyder, Neugebauer, and Rao, 1963]. The physical linkage between the two measures of the outer zone profile is presumably the radial diffusion of ~ 1 MeV electrons as reported by Frank [1965], the average rate of diffusion being apparently greater and/or the mechanism for radial diffusion penetrating more deeply into the magnetosphere during periods of higher average solar activity.

The solar-cycle variation of atmospheric density [King-Hele and Rees, 1965] is quantitatively inadequate [Van Allen, 1964] and of the wrong algebraic sign to account for the outward movement of the outer-zone profile.

Also it may be noted that the typical magnitude of the peak intensity of energetic electrons ($E_e \gtrsim 1$ MeV) in the outer zone near the geomagnetic equator as observed by Pioneers 3 and 4 [Van Allen and Frank, 1959a, b], Explorer 12 [Freeman, 1964], Explorer 14 [Frank, Van Allen, and Hills, 1964], and OGO 1 [Frank, Van Allen, Hills, and Fillius, 1965] has not displayed a marked change during the decreasing portion of the solar activity cycle, perhaps indicating a 'saturated' magnetosphere with regard to the population of $\sim$ 1 MeV electrons.

In the framework of the present discussion, it is anticipated that the L-profile of the outer zone will move back inward toward the earth during the next several years of expected increase in solar activity.

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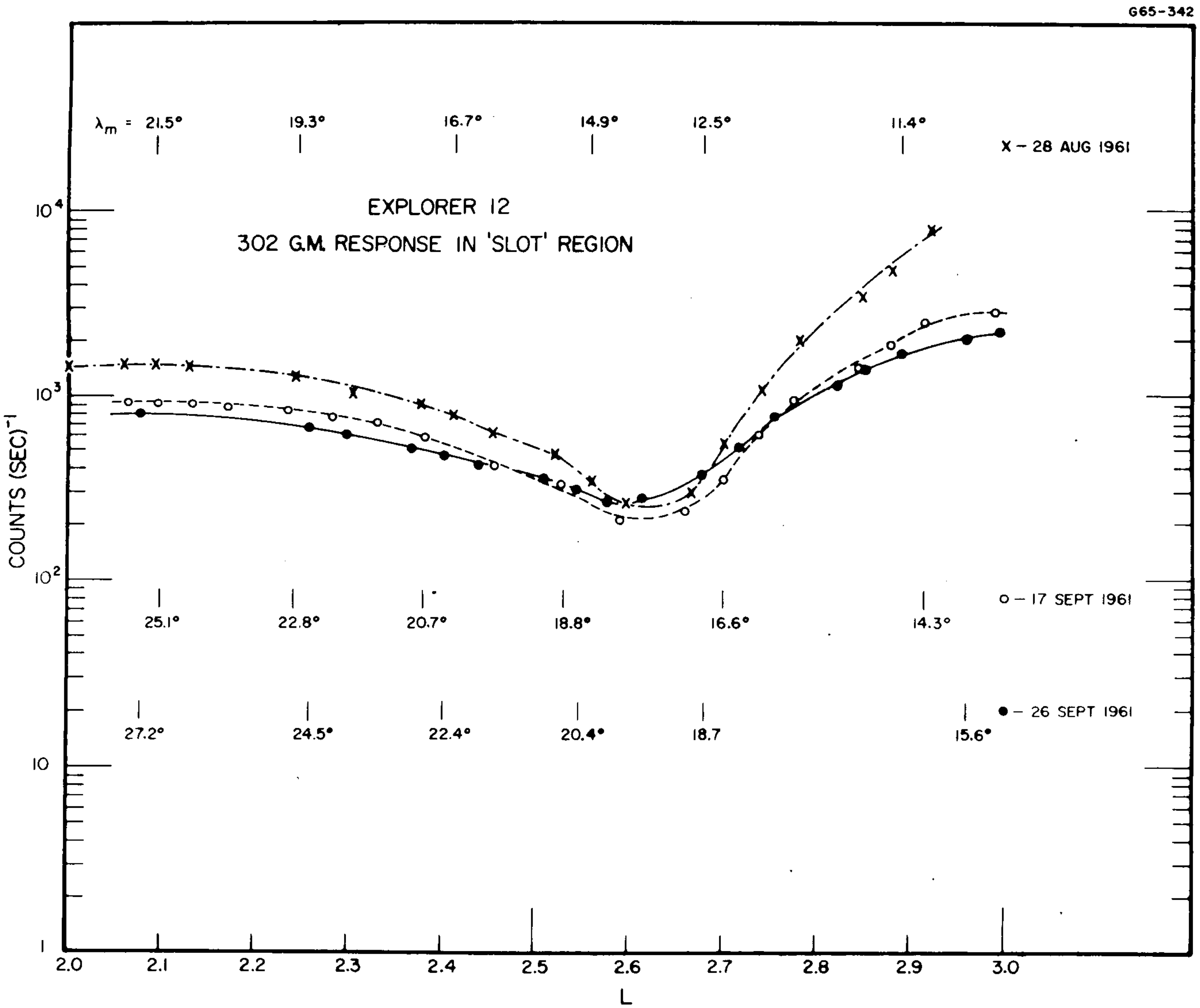
FIGURE CAPTIONS

Figure 1. Response of the 302 G.M. tube for several similar passes of Explorer 12 through the 'slot' region between the inner and outer radiation zones.

Figure 2. Summary of the positions of the inner edge of the outer radiation zone (electrons $E_e \gtrsim 1$ MeV) as observed with similar detectors in various spacecraft over a six year period. A measure of solar activity is given by the parallel plot of smoothed sunspot numbers.



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EXPLORER 12
302 G.M. RESPONSE IN 'SLOT' REGION
λ_m = 21.5°
19.3°
16.7°
14.9°
12.5°
11.4°
X – 28 AUG 1961
25.1°
22.8°
20.7°
18.8°
16.6°
14.3°
o – 17 SEPT 1961
27.2°
24.5°
22.4°
20.4°
18.7
15.6°
● – 26 SEPT 1961
COUNTS (SEC)$^{-1}$
10^4
10^3
10^2
10
1
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
L

Figure 1

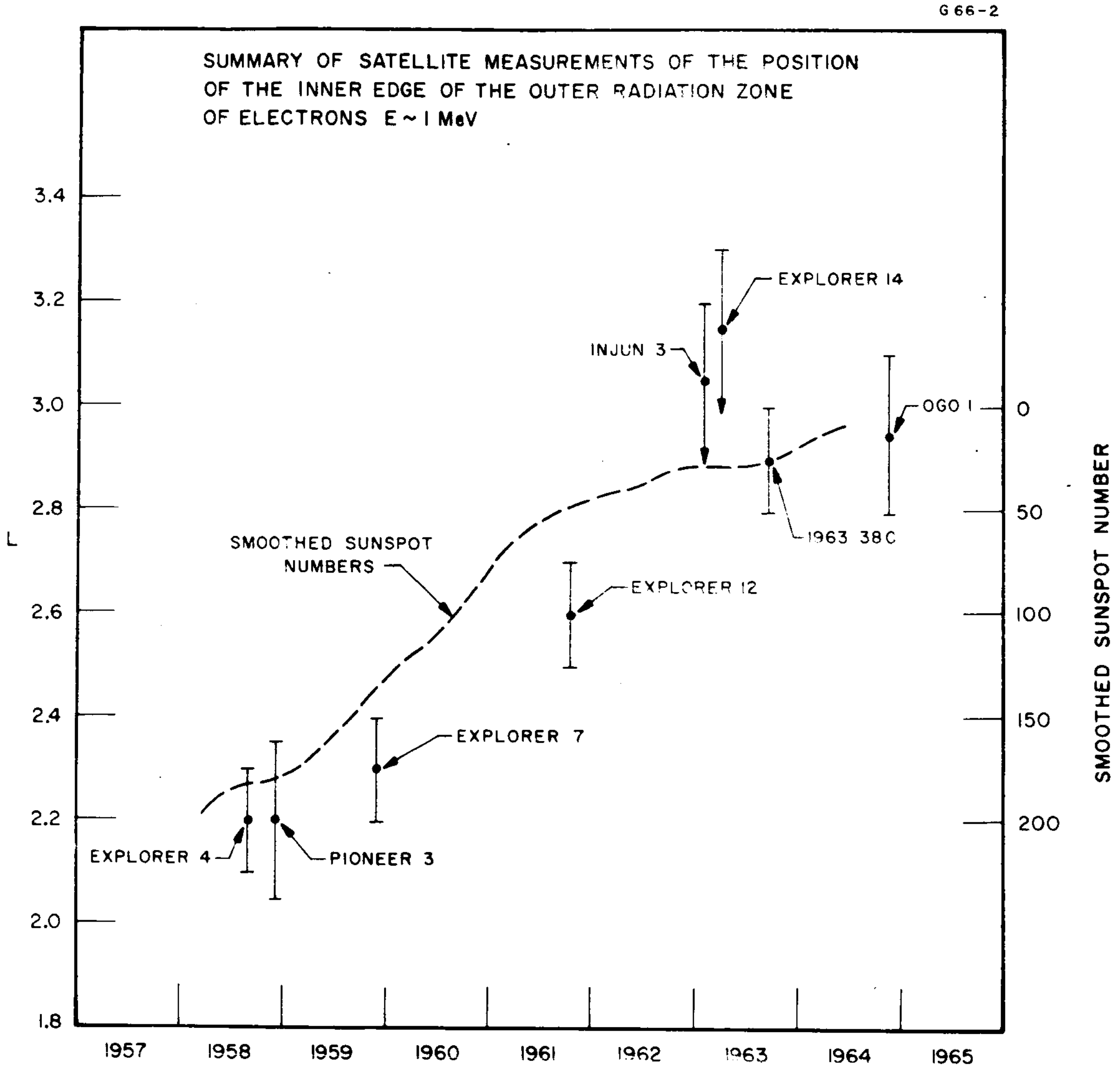
G 66-2
SUMMARY OF SATELLITE MEASUREMENTS OF THE POSITION
OF THE INNER EDGE OF THE OUTER RADIATION ZONE
OF ELECTRONS E ~ 1 MeV
L
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1957
1958
1959
1960
1961
1962
1963
1964
1965
SMOOTHED SUNSPOT NUMBER
0
50
100
150
200
EXPLORER 14
INJUN 3
OGO I
1963 38C
SMOOTHED SUNSPOT NUMBERS
EXPLORER 12
EXPLORER 7
EXPLORER 4
PIONEER 3

FIGURE 2

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A comparison of observations with several earth satellites reveals that the inner edge of the outer radiation zone of electron $E_e > 1.6$ MeV intensities has moved outward from $L \simeq 2.2$ in mid 1958 to $l = 3.0$ in late 1964. This outward motion of the outer radiation zone occurs during the declining phase of solar activity cycle 19 and strongly suggests a systematic change of the average value of one or more of the solar wind parameters over this time period.

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